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Prestressed concrete research at Lehigh University 1952-1958, (Special Report No. 8), Lehigh University, (March 1959)

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To: Lehigh Prestressed Concrete Committee

From: Carl E. Ekberg, Jr.

Special Report No. 8, entitled "Prestressed Concrete Research at Lehigh University 1952 - 1958", contains a resume of all of the work done under the auspices of the LPCC since its inception. It is my intention to submit this report to ACI, ASCE, or to some other similar organization for possible publication, and I would like to suggest that you send me your criticisms or comments before June 1, 1959.

If, in the meantime, you need any additional copies, please let me know.

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Fritz Engineering Laboratory
Structural Concrete Division

SPECIAL REPORT NO. 8

PRESTRESSED CONCRETE RESEARCH

AT

LEHIGH UNIVERSITY

1952 - 1958

by

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and

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March 1959

PURPOSE

It is the purpose of this report to describe the research work which has been carried out by the Structural Concrete Division in Fritz Engineering Laboratory in the years from 1952 through to 1958. Much of this work has been of a quite specialized nature and it is intended here to indicate, in a general manner, the problems that have been studied, some of the more important results which have been obtained and the source references for detailed information on each phase of the work.

ACKNOWLEDGMENTS

The staff of the Structural Concrete Division gratefully acknowledge the cooperation and assistance over the past six years of the members of the Lehigh Prestressed Concrete Committee.

The authors are indebted to Mr. Thor Germundsson, Chairman of the Reinforced Concrete Research Council, for his encouragement and constructive criticism during the preparation of this report.

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INTRODUCTION

On May 15, 1951, Professor W. J. Eney and Professor A. C. Loewer of Lehigh University proposed a program of research to the following organizations:

Pennsylvania Department of Highways
Bureau of Public Roads
Reinforced Concrete Research Council
Research Corporation
Concrete Products of America *
John A. Roeblings' Sons Corporation
American Steel and Wire Div., U.S. Steel Corporation

The proposal was entitled "Analysis of Full-Scale Precast Prestressed Bridge Members under Repetitive Loads" and the objectives of the program were to test and analyze full size pretensioned and post-tensioned prestressed concrete bridge members, under simulated highway traffic loads.

The research was commenced on September 1,1951 , in anticipation of the subsequent approval. To guide the work,

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* Later became the American-Marietta Company, Concrete Products Division.

the sponsoring organizations appointed representatives to a committee which became known as the Lehigh Prestressed Concrete Committee, or LPCC. The first meeting of the LPCC took place at Lehigh University on July 8, 1952 *

In the years immediately following its formation, the LPCC considerably widened its objectives to include, besides the testing of full-scale bridge members, an examination of the lateral load distribution in multi-beam bridges and an extensive study of the fundamental properties of prestressed concrete beams. The concrete research at Lehigh which has been sponsored by the LPCC, thus consists of three main phases:

I. Large scale testing of prestressed members.

II. Theoretical and experimental work on the lateral load distribution in multi-beam bridges.

III. Studies of fundamental beam behavior.

From 1952 to 1956 attention was concentrated on phases I and II. When the major portion of this work was nearing completion an experimental study of the bonding characteristics of wire strand was commenced. All of the projects within the first two phases have now been completed and the bond investi-

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* The only change in membership of the LPCC occurred shortly after its inception in 1952 when the Research Corporation withdrew.

gation will be terminated in the near future.

In 1957 and 1958 analytic studies were made of the ultimate strength of beams under the combined action of moment and shear and of the fatigue strength of flexural members. Both of these projects were extended to include experimental work which constitutes the major portion of the present work.

Each of the phases is described in the following text. More detailed information on any one portion of the research is available in the form of progress reports and, often, in papers presented to technical journals and professional institutions. A complete list of progress reports and publications is provided in the appendix. References throughout the text correspond numerically to this list.

PHASE I: LARGE SCALE TESTING OF PRESTRESSED CONCRETE MEMBERS

Before new information and techniques can be applied with confidence in the field, tests involving full-scale structures are a necessary supplement to the experimental work which is carried out using small-size laboratory test specimens. It was for this purpose that these large-scale tests, the first in the United States, were conducted.

The original program included a series of five pilot tests on small beams, the design and assembly of a repetitive load machine and the testing of two 38 ft span prestressed concrete beams. In addition to this a number of independently sponsored tests have been carried out on beams of rectangular and box sections, with spans up to 70 ft under both static and dynamic loadings.

Pilot Tests

In preparation for the large-scale tests, a series of five pilot beams of 12 ft length were tested during the first year of the program. The main purposes were to perfect testing techniques and to allow the investigators to observe the physical behavior of prestressed concrete beams. Three of the beams were pretensioned, a fourth was post-tensioned and the fifth was conventionally reinforced. In conjunction, a number of pullout tests were carried out on 5/16 in. diameter prestressed strands embedded in rectangular concrete blocks. The work is described in Progress Reports 1 through 4, and in a paper based on Progress Report 4, dealing with the use of electric resistance strain gages on steel strands embedded in concrete. See References 1-5 inclusive.

Repetitive Load Machine

For testing large prestressed members, a repetitive load machine was designed and constructed. In the testing arrangement a load was applied to the specimen at each third point through a yoke connected to a standard hydraulic jack. A sinusoidal loading cycle was achieved by means of a high pressure pump drawing oil from a reservoir and pumping it to the jacks through a system of high pressure pipe lines and valves.

An electronic timing device, connected to the principal four-way valve, controlled the time of loading and unloading. The complete loading cycle could be varied between a quarter of a second and four minutes.

The machine normally operated with two conventional hydraulic jacks, each having a capacity of 50,000 lbs. In order to determine the applied forces, strain gages were mounted on the rods connecting the jack with the loading yokes. A conventional type SR-4 strain indicator was used during static testing, while a Brush Recorder with amplifiers was used during repetitive loading.

A detailed account of the machine may be found in Reference 8. The machine was used in the two full-scale beam tests called for in the original proposal and by the end of 1953 had successfully applied a total of 2,500,000 repetitions of heavy loading.

In 1955 considerable extensions were made to the floor space and facilities of Fritz Laboratory. The addition of a dynamic test bed coupled with the purchase of a set of Amsler jacks and pulsators has somewhat outmoded the alternating load machine by reason of greater versatility and ease of assembly. Since its installation the new equipment has been used in all the large-scale tests carried out. The design and construction of the test bed and the static and dynamic loading apparatus are described in Reference 12.

Endurance Tests of Full-Scale Prestressed Concrete Members

In the period between August 1952 and July 1953 two prestressed concrete beams of 38 ft span were endurance tested. In these tests the repeated loading was equivalent to the effect of the maximum number of design loadings that a corresponding bridge member might be expected to experience in the course of its service life. The tests served as a check on the adequacy of design assumptions at working load, cracking load, and ultimate load.

The magnitude of the loading was chosen on the basis of the 1949 AASHO "Specifications for Highway Bridges" and traffic volume surveys were used to determine the number of applications. The loading arrangement used for both beams, which is shown in Figure 1, simulates H20-S16 loading with a 30 percent impact factor.

Pretensioned Beam

The first specimen to be tested was a hollow, rectangular pretensioned beam of overall cross section 36 in. wide and 21 in. deep. The details of the beam are shown in Figure 4. Two circular hollow cores of 12-1/2 in. diameter extended side by side throughout the length of the beam except for solid portions at ends and at midspan. The reinforcement consisted of 40 pretensioned, bonded strands of 5/16 in. nominal diameter and an assembly cage of conventional steel.

An outline of the testing program for this beam is presented in Figure 6. The procedure consisted of an initial static test under the equivalent design load, followed by 300,000 cycles of repetitive load applied at the rate of one cycle per sec. This sequence was repeated until a total of 1,300,000 cycles of design load and six static tests had been carried out. A static test at 154 percent of equivalent design load was conducted and was followed by 100,000 repetitions of the same load. At this stage the beam showed no appreciable evidence of distress and it was loaded to destruction in a final static test.

Post-Tensioned Member

The post-tensioned test member, shown in Figure 5, was composed of two I-shaped beams bolted together at the center, the quarter points and the ends. The beams were 26 in. high with a top flange width of 18 in. and a bottom flange width of 12 in. The reinforcement in each beam consisted of one 1 in. diameter, and two 0.60 in. diameter unbonded post-tensioned cables and an assembly cage of conventional reinforcing bars. The prestressing cables were held by anchorages at each end of the beam and were coated with grease and wrapped with sisal-craft paper to prevent any bond between concrete and cable.

The loading arrangement was similar to that of the pre-tensioned member described in Figure 1.

A total of 1,000,000 repetitions of design load were applied, interspersed between four static tests to design load. This was followed by static tests to 280 percent of design and to failure. The complete test program is shown in Figure 7.

Significance of First Full-Scale Tests

These first repetitive load tests of large beams indicated a satisfactory performance for the number of cycles corresponding to the life of a bridge, and undoubtedly helped to encourage the application of prestressed concrete to bridge construction. Large numbers of engineers visited the Fritz Engineering Laboratory to witness the tests and the results were made available to many more through References 6, 7 and 8.

PHASE II: LATERAL LOAD DISTRIBUTION IN MULTI-BEAM BRIDGES

Prior to 1954, it was customary to assume only a limited interaction between the component members of a multi-beam bridge. Thus, each beam was designed for 80 percent of the standard design wheel load. Such methods produced unnecessarily heavy bridge members and indirectly limited the use of this type of construction to bridges of short span lengths.

The research work on multi-beam bridges began in July, 1954 with field tests on a highway bridge in service. A theoretical analysis of load distribution was then made and was followed by a series of laboratory tests on a specially constructed scale model bridge of 16 ft span.

The over-conservative nature of the current design procedures was demonstrated by this work, which resulted in a lowering of the design factor required by the Pennsylvania Department of Highways from 80 percent to 60 percent. The extensive numerical computations required in the theoretical analysis were carried out in the "Univac" computing machine of the Remington Rand Corporation, New York City. The resulting tables of distribution factors can be used directly in the analysis and design of bridges of various size under the more critical loading conditions.

Field Tests

The field tests were carried out on a highway bridge 27 ft wide, with a clear span of 32 ft. An overall view of the structure is shown in Figure 8. The bridge was composed of nine precast, pretensioned concrete beams connected together with dry-packed continuous shear keys.

The principal portion of the tests consisted of measuring the deflected shapes of the bridge due to varied truck loadings placed at critical positions on the bridge.

A typical mid-span deflection diagram is shown in Figure 9. This corresponds to the loading obtained by two jacks transmitting a rear axle load of 47,700 lbs. to the central beam in the bridge. The maximum deflection in this case occurred under the load points and was only 0.0715 in.

Approximate values for the lateral load distributions were calculated from the relative beam deflections. For example, Figure 10 gives the load distribution which was calculated from the deflections shown in Figure 9. The full details of the field tests may be found in References 13 and 14.

Theoretical Study

In the theoretical analysis it was assumed that:

(a) There is no relative slip between adjacent beams

(b) The bridge, as a whole, acts as an orthotropic plate.

The equation of the orthotropic place is

$$\frac{\partial^4 w}{\partial x^4} + 2\beta \frac{\partial^4 w}{\partial x^2 \partial y^2} + \alpha \frac{\partial^4 w}{\partial y^4} = \frac{p(x,y)}{EI_x}$$

where p(x,y) is the load function, and w is the deflection in the z-direction at a point (x,y). The orientation of coordinate axes is such that the x-axis coincides with the longitudinal axis of the central beam, and the y- and z-axes are directed laterally, and vertically downward. EI_x and EI_y are the bending stiffness per unit width in the x- and y- directions, respectively.

The following expression was assumed for the torsional coefficient β,

$$\beta = 3K(1 - \alpha^{1.5}) + \alpha$$

where K is the constant of torsional rigidity of a single beam and $\alpha = \frac{EI_y}{EI_x}$. In the limiting cases of an articulated and an isotropic plate the values of α are respectively zero and unity, and the values of β reduce to 3K and unity.

The differential equation was solved for the boundary conditions corresponding to a simply supported bridge and the resulting equations for deflections, moments and forces were evaluated for loadings applied at mid-span.

Coefficients of lateral load distribution were also evaluated and tabulated for bridges of various dimensions in such a way that various loading conditions can be considered. The theoretical work and the tables of design data are contained in Reference 15.

Tests and Analysis of a Laboratory Bridge

In this investigation nine prestressed concrete beams were connected together by tensioned transverse bars at the center, quarter points, and supports to form a multi-beam bridge 10 ft-9 in. wide with a 16 ft span. Details are shown in Figure 11. The lateral post-tensioning was adjustable to any required value.

The principal objective of the tests was to substantiate with experimental data the theory of multi-beam bridges referred to in the previous section of this report. To accomplish this a total of 58 tests were performed on the bridge and its component members. These may be divided into the following categories.

1. Tests to determine the stiffness properties of the bridge:
   - (a) Flexural stiffness and other properties of the individual beams.
   - (b) Longitudinal bending stiffness of the bridge
   - (c) Lateral bending stiffness of the bridge

(d) Torsional rigidity of the bridge

2. Tests to investigate the influence of the following:

   (a) Degree of lateral post-tensioning

   (b) Location of the lateral post-tensioning bars

   (c) Interaction of the shear keys

   (d) Location of the external load

   (e) Slip between adjacent beams

3. Tests to determine the lateral distribution of overloads in the inelastic range and at failure of the bridge.

A general view of the test arrangement may be seen in Figure 12. A static load is being applied to the mid-point of the bridge and a technician is checking for slip between adjacent beams. The ends of the transverse post-tensioning bars are visible on the left-hand side together with a hydraulic jack supported in position on the central bar for the purpose of changing the tension. A network of dial gages for recording the bridge deflections may be seen beneath the bridge.

Satisfactory correlation of the test data with the theory was obtained. In addition, information of an empirical nature was obtained on relative slip between adjacent beams and modifying parameters were derived for use when the possibility of slip occurs. References 16, 17 and 18 give results of this work.

PHASE III: FUNDAMENTAL PROPERTIES OF PRESTRESSED CONCRETE MEMBERS

The work in this phase has consisted of three fundamental studies:

(a) The bonding characteristics of steel strands in pretensioned beams

(b) The fatigue resistance of prestressed concrete flexural members

(c) The strength of prestressed concrete members under the combined actions of bending and shear.

Bond in Pretensioned Prestressed Members

The bond study has been concerned with obtaining an understanding of anchorage failures and flexural bond failures in beams containing pretensioned wire strands. Anchorage failure is said, in this context, to occur when the bond between the steel and concrete, in the region of the beam extending from the outermost crack to the adjacent end, breaks down. Flexural bond failure occurs in the inner portion of the beam at the regions of high moment and shear.

A novel feature of the experimental work was the development of a technique for "pull-in" testing to simulate the stresses induced in the anchorage zone of a beam under an applied moment.

The steps in the procedure are outlined shematically in Figure 13. The experimental study involved a total of 32 static beam tests and 42 pull-in tests.

From the tests it was concluded that flexural bond failure is rarely critical in the normal designs in which steel strands are used. Although the degree of vibration and compaction of the wet concrete was not a major variable, it was observed that this has a much greater influence on the resulting bond than is customarily considered.

The general results of the bond program are available in Reference 23, together with proposed criteria to assure safety against bond failure. The particular test data is contained in References 19 through 22.

Fatigue Resistance of Prestressed Concrete Beams in Bending

The failure of a prestressed concrete flexural member as a result of a repeated system of loading can occur by the fatigue-ing of either or both of the component materials, i.e., high strength steel and concrete. A theory has been developed which, it is believed, gives a reasonably accurate estimate of fatigue strength due to steel failure and which gives a lower bound to the value of fatigue strength due to concrete failure.

The theory, as originally derived, provides a means of predicting whether or not a given range of loading, when repeated for one million cycles, will cause failure. Use is made of the fatigue failure envelopes of the component materials and the stress-moment relations for the cross-section of the member. The theory is presented in detail in References 24 and 25.

A number of important conclusions follow from the theory. For example, it can be shown that the normal static "balanced" design will in almost all cases be under-reinforced from the point of view of obtaining simultaneous failure in the concrete and steel under repeated loadings. Calculations made using this theory have also indicated that there can be a reduction in ultimate moment of as much as 30 percent if a repeated rather than a sustained loading occurs. This, of course, does not mean that fatigue failure will occur in properly designed members under design loads; however, it does imply that the occurrence of a number of overloads which cause cracks to open, can significantly reduce the factor of safety from the value obtained on the basis of the static ultimate strength.

The results of the large scale tests, given in References 6, 7 and 8, together with the results of a number of tests on laboratory specimens have given satisfactory agreement with the theory. However, a detailed analysis of all available fatigue test data is at present being made to substantiate the theory. Further theoretical work on fatigue failure is contemplated, the main purposes of which would be to provide an "exact" solution for the concrete fatigue failure and to clarify the problem of defining and determining the "factor of safety" of members under varied repeated loadings.

Shear Strength of Prestressed Concrete Members

A study of the resistance of prestressed concrete to combined bending and shear was begun in 1956 with a theoretical analysis of the "shear compression" failure which is commonly observed in laboratory tests. An approach was made by applying Mohr's failure criterion to the compressive stress block in the upper portion of the beam at the critical section and combining the equations for critical stresses with the equations of static equilibrium. A compatibility condition was assumed which consisted of a "shear rotation" about the neutral axis at the critical section coupled with a pull-out effect of the longitudinal tension steel relative to the surrounding concrete. The mathematical expression of the compatibility condition, in terms of deformations in steel and concrete, was combined with the equations of equilibrium and critical stresses to give an analytic solution for the ultimate strength. The theoretical analysis was completed in 1957 and is reported in References 26, 27 and 28.

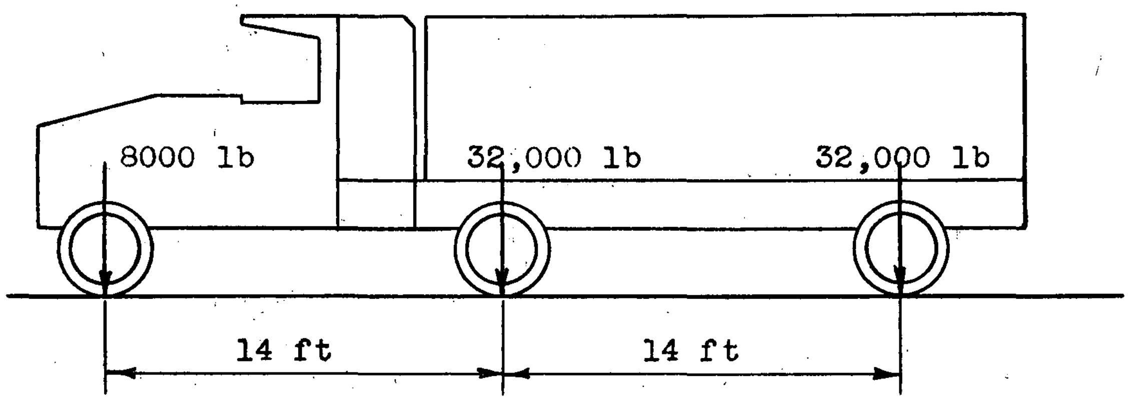
In 1958 an extensive experimental program was begun. The first stage, which has now been completed and reported in Reference 29, demonstrated experimentally the effect on shearing strength of:

(a) Level of prestress

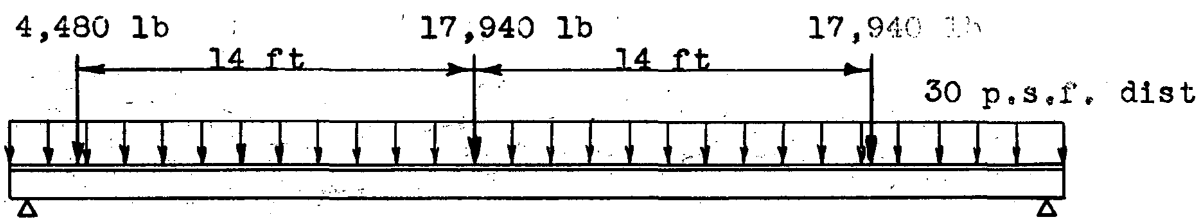
(b) Condition of the bond between the longitudinal steel and the surrounding concrete.

At present an evaluation of the data in the light of the theoretical work is being made. In the future a study will be made of the conditions under which shear failure can precede flexure failure; this, it is hoped, will lead to more realistic procedures for the design of shear reinforcement.

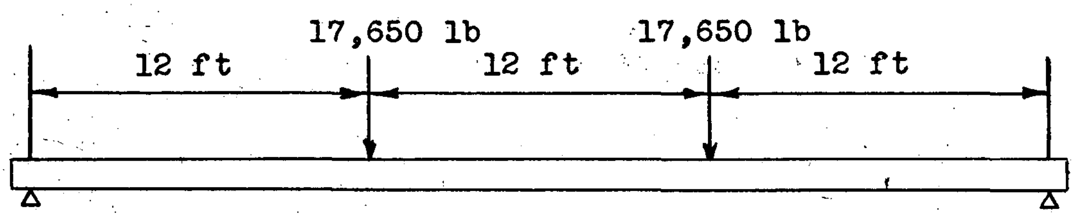
The second stage of the experimental program is presently in progress. One of the aims is to determine whether or not important differences exist between shear failures occurring under the standard loading conditions used in the laboratory, and those under the loading conditions which can occur in practice. The other main aim in this portion of the tests is to obtain experimental data on the failure mechanism in shear compression and in particular on the compatibility condition at the instant of failure.



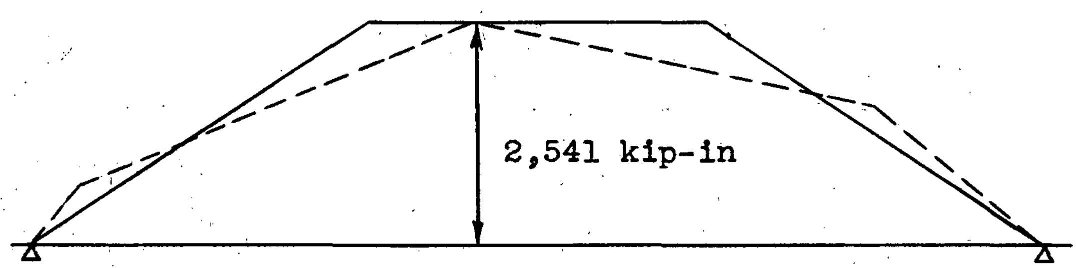
a. Actual AASHO H20-S16-44 Bridge Loading



b. H20-S16-44 Loading, including 30% impact, for Single Beam



c. Equivalent Experimental Loading



d. Comparison of Design Loading and Experimental Loading

Fig. 1. LOADING DIAGRAMS FOR FULL-SCALE TESTS

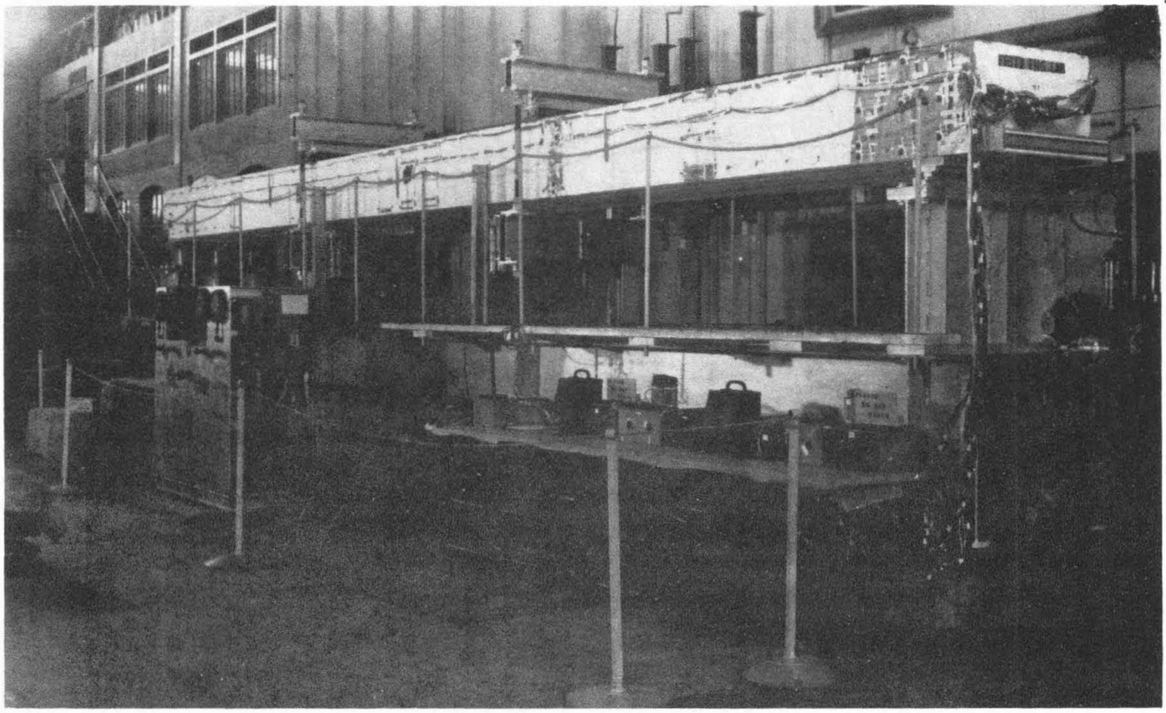


Fig. 2. REPEATED LOAD TESTS ON 38 FT. SPAN PRETENSIONED MEMBER

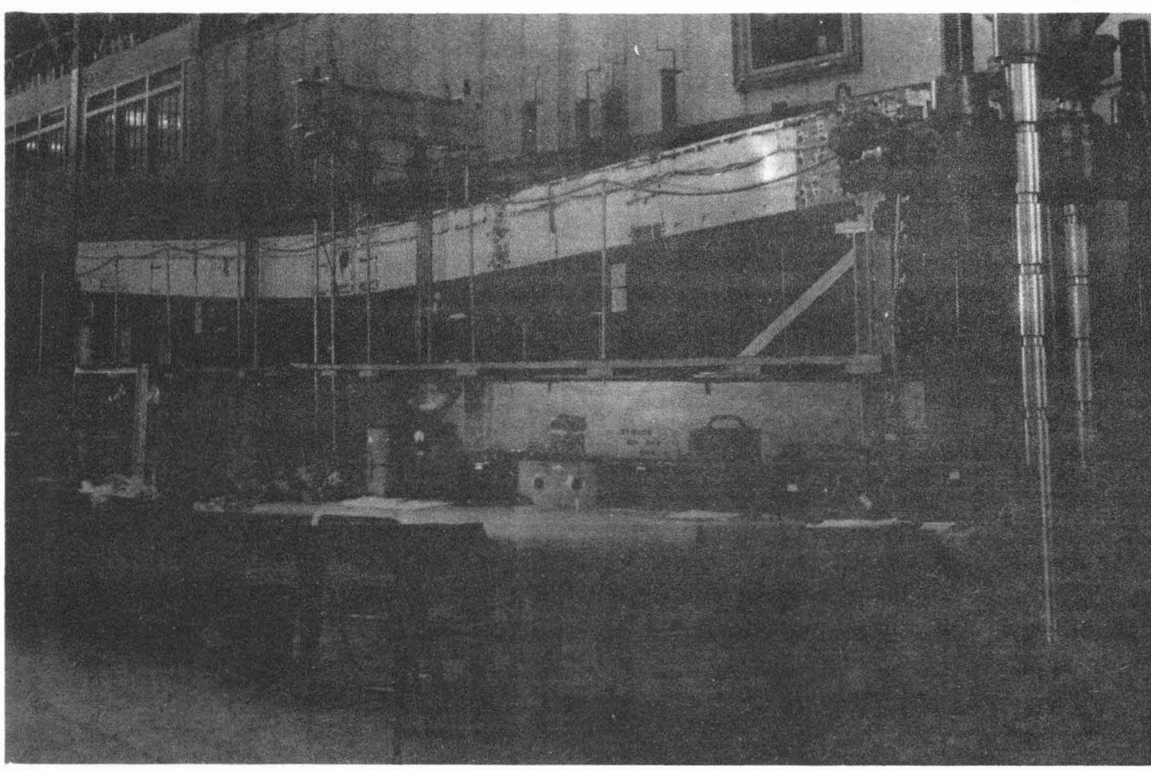


Fig. 3. STATIC DESTRUCTION TEST OF 38 FT. SPAN POST-TENSIONED MEMBER

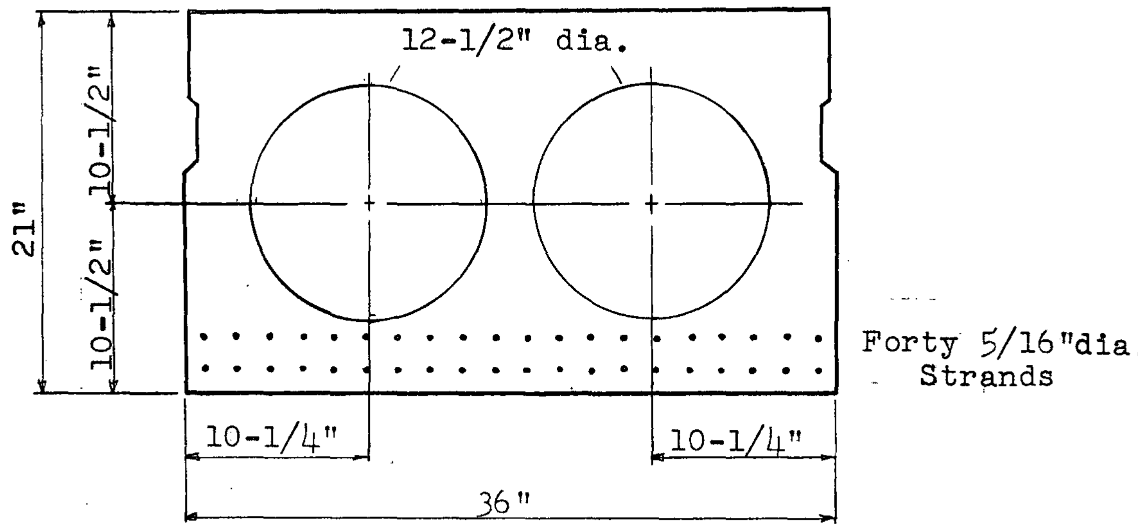


Fig. 4 - CROSS SECTION OF 38-FT. SPAN PRETENSIONED MEMBER

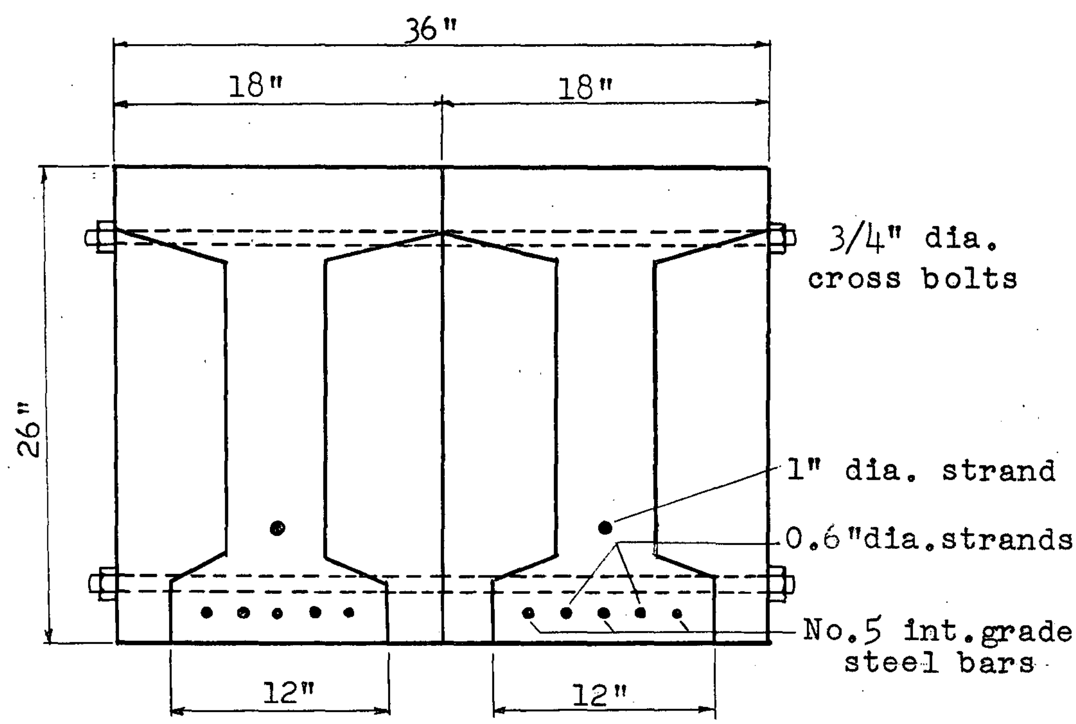


Fig. 5 - CROSS SECTION OF 38-FT. SPAN POST-TENSIONED MEMBER

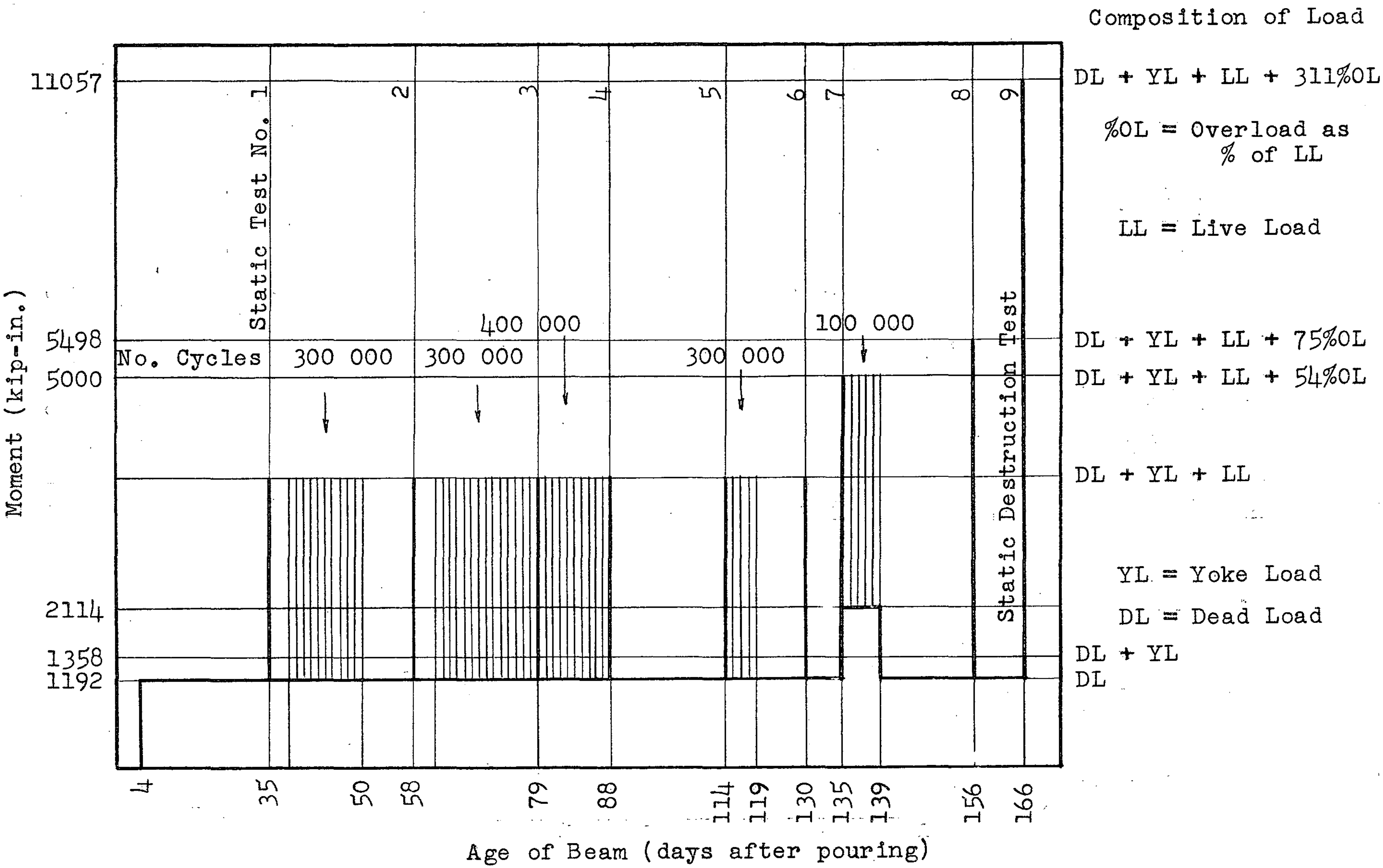


Fig. 6 - TEST PROGRAM FOR PRETENSIONED MEMBER

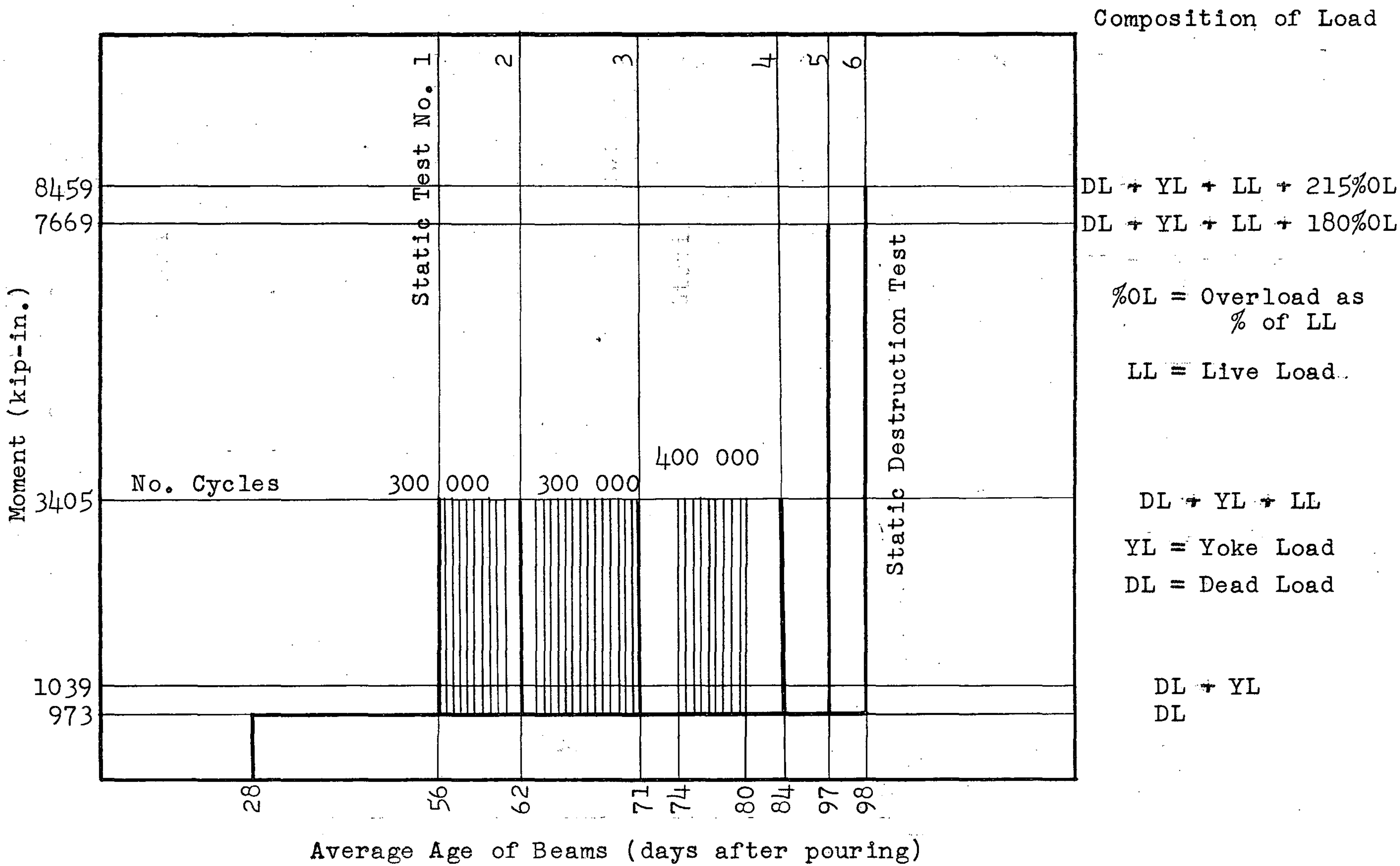


Fig. 7 - TEST PROGRAM FOR POST-TENSIONED MEMBER

Fig. 8 OVERALL VIEW OF HIGHWAY BRIDGE

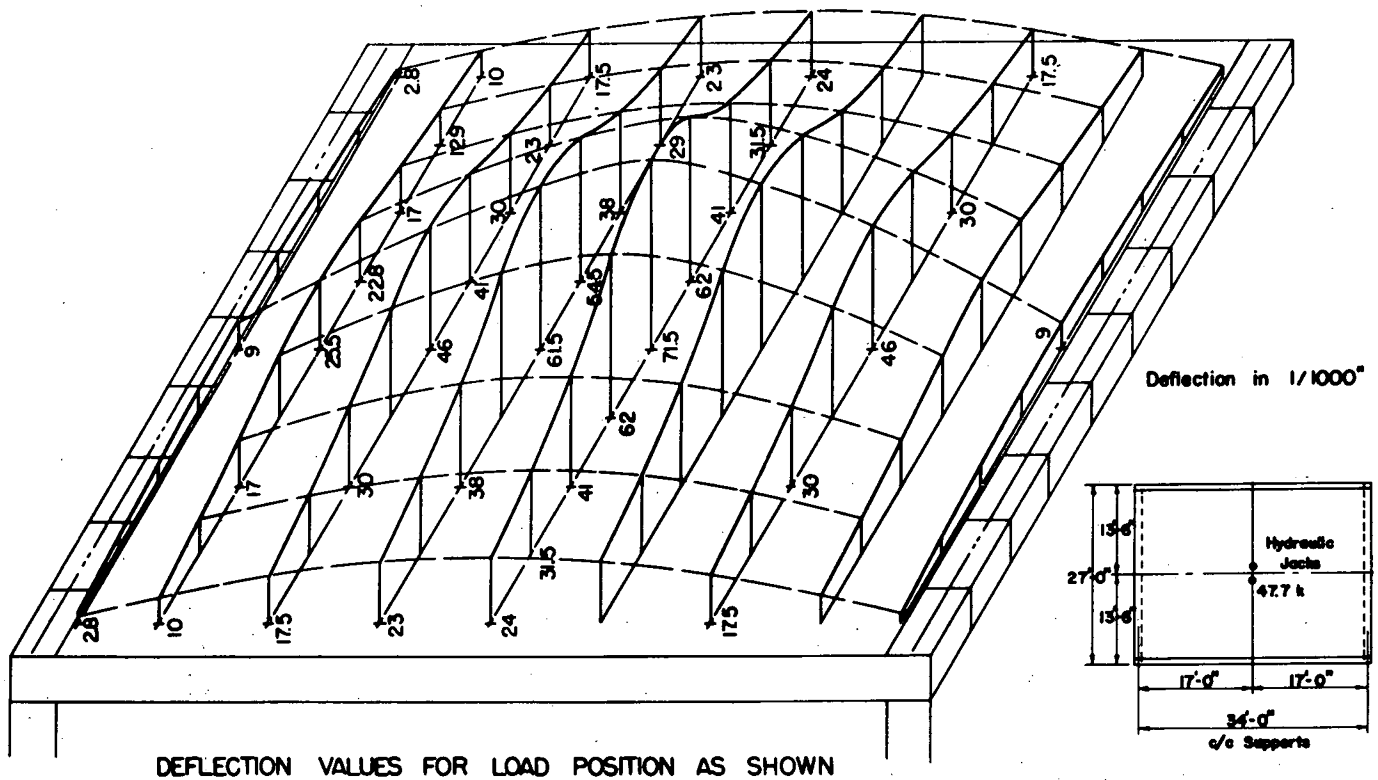


Fig. 9. TYPICAL DEFLECTION DIAGRAM FROM FIELD-TEST OF BRIDGE

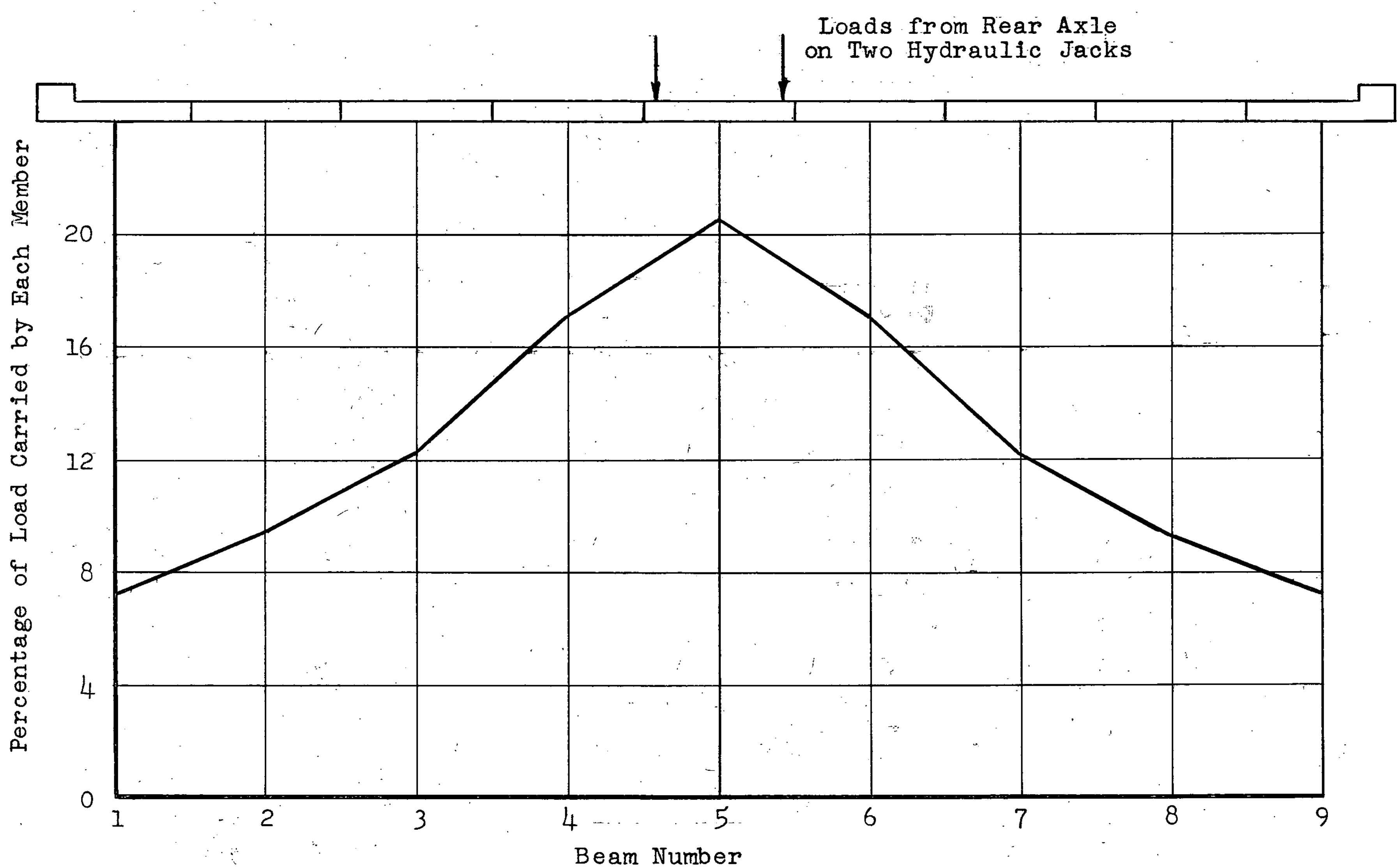


Fig. 10 -APPROXIMATE DISTRIBUTION OF LOAD TO INDIVIDUAL BEAMS

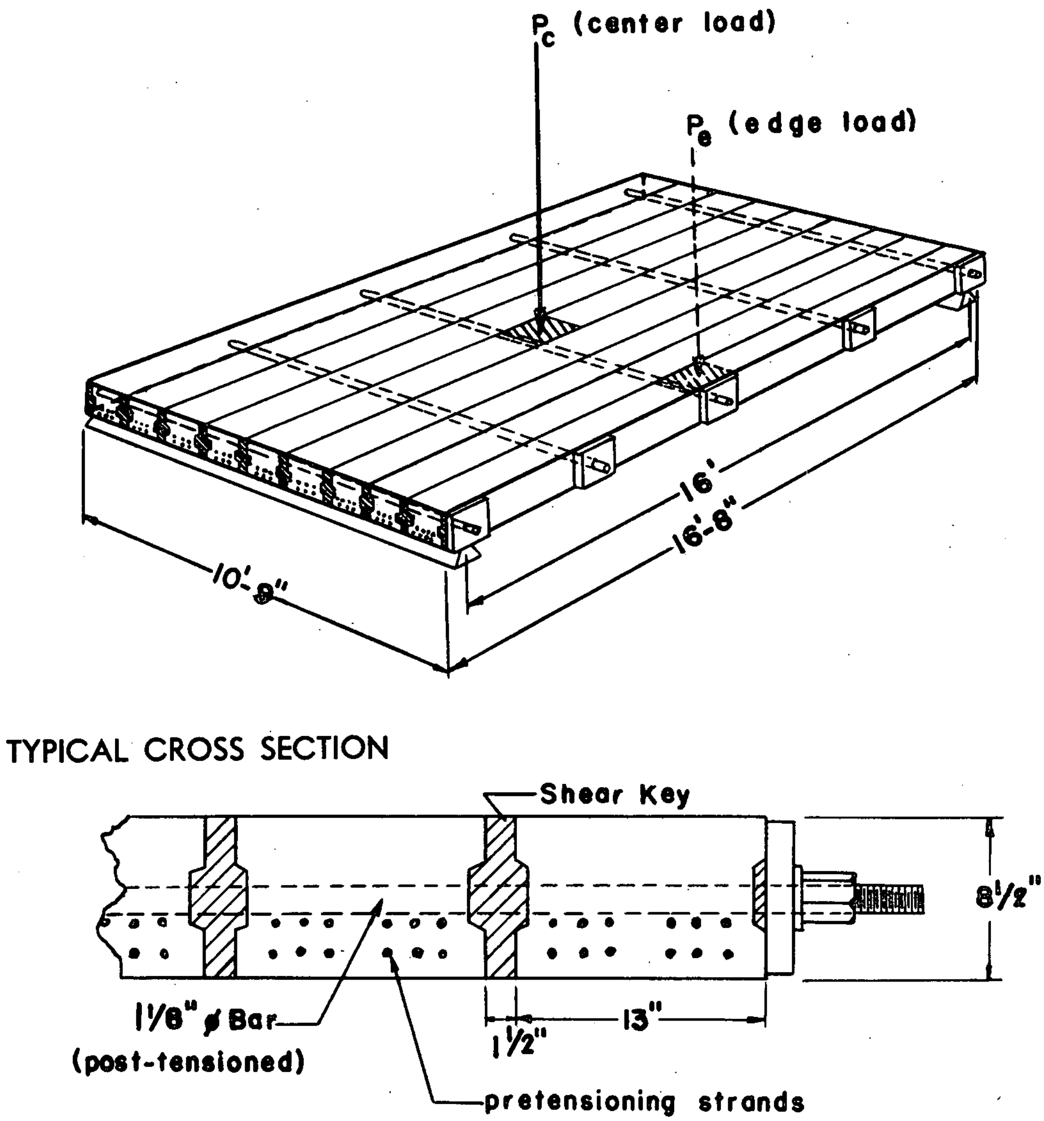
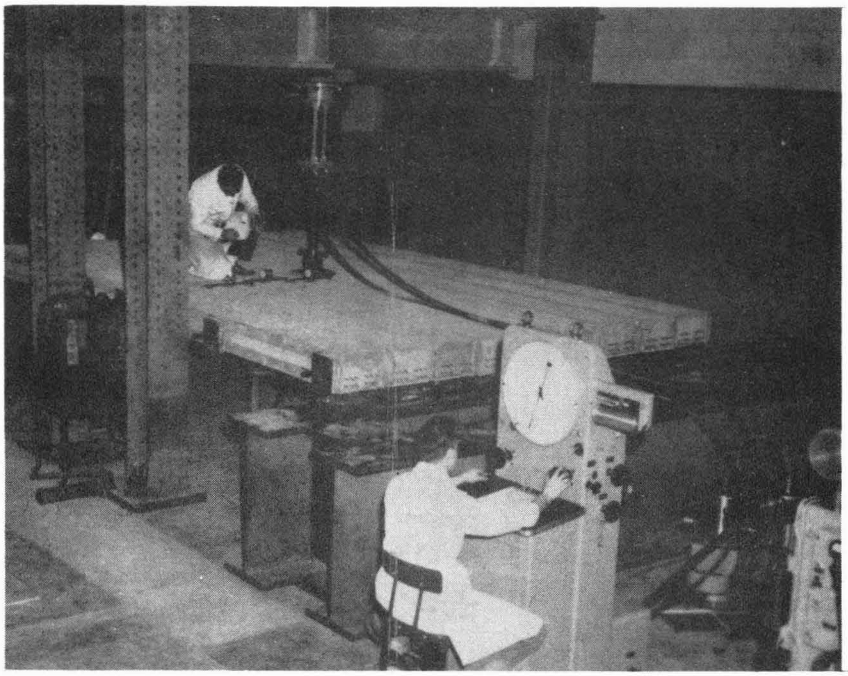
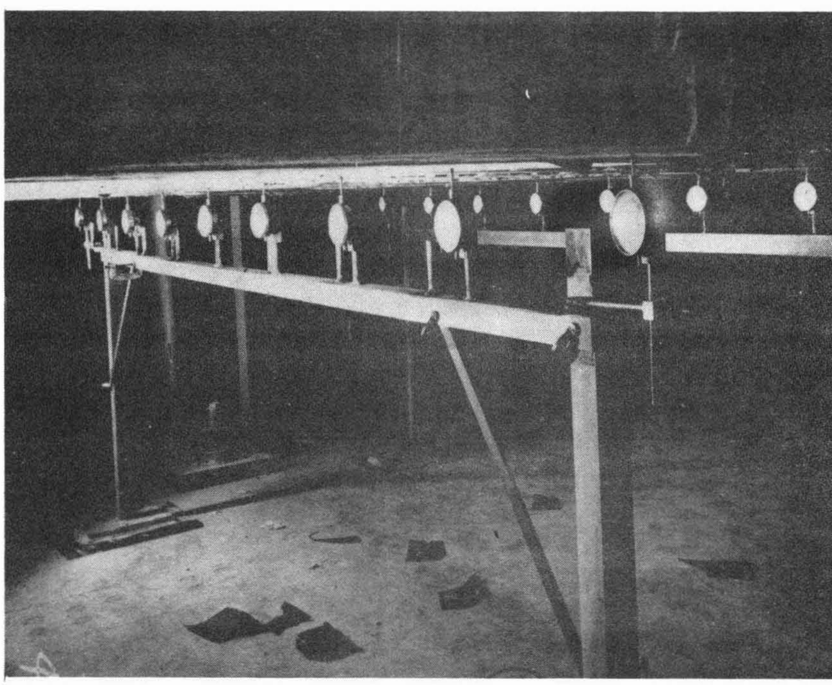


Fig. 11. THE LABORATORY BRIDGE

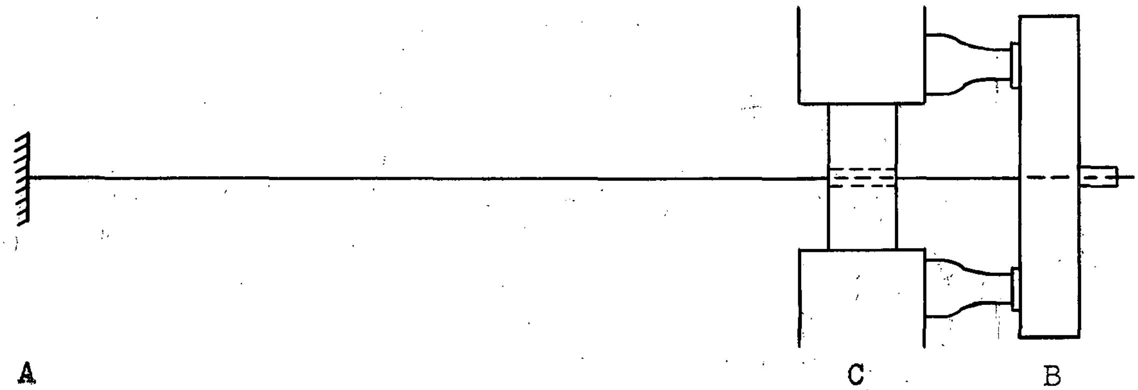


General View

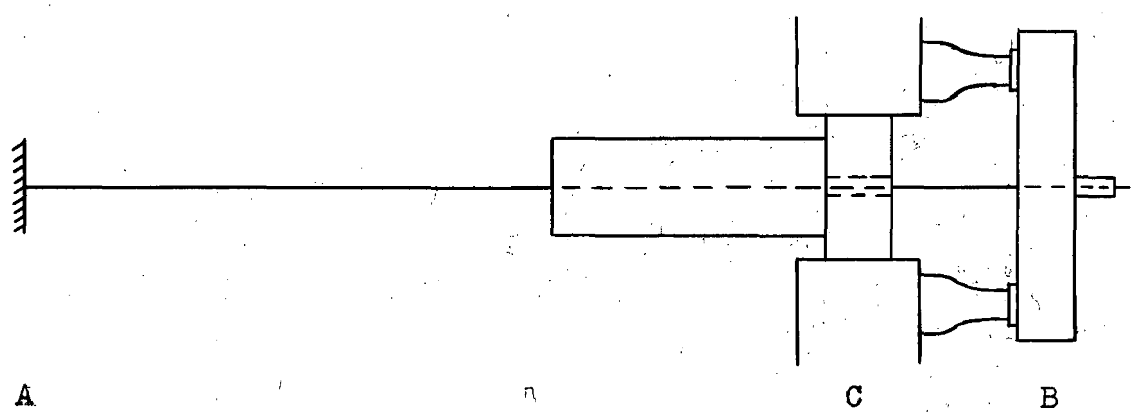


Dial Gages for measuring the bridge deflections

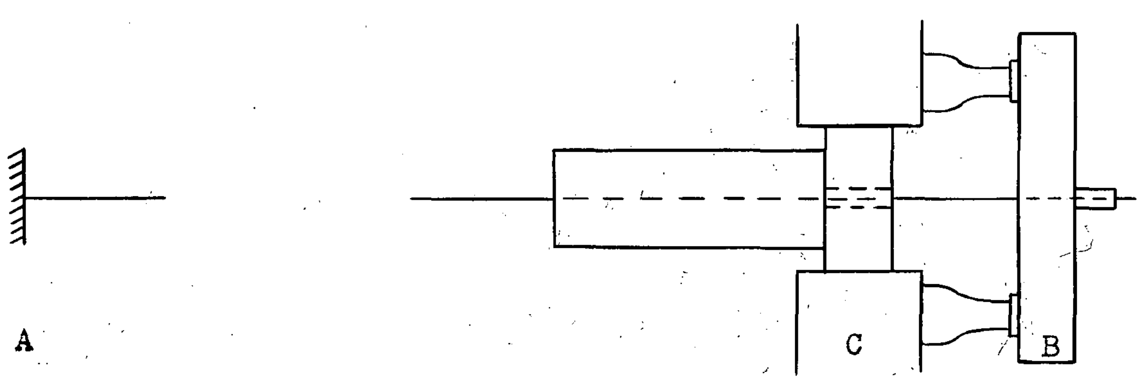
Fig. 12. TEST ARRANGEMENT FOR LABORATORY BRIDGE



Step 1. Strand is prestressed between fixed cross-head A and movable cross-head B.



Step 2. Concrete is poured around the pretensioned strand, against the fixed cross-head C.



Step 3. Strand is cut at end A, the cross-head B is jacked away from fixed cross-head C

Fig. 13. BOND PULL-IN TESTS

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